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## Smart Workload Balancing

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# Smart Workload Balancing

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**Abstract.** The cognitive workload of operators working with automated systems should neither be too high nor too low. A static level of automation is unable to cope with systems that produce large fluctuations in cognitive workload, therefore a method for adaptive automation is proposed that could balance workload by intelligently choosing what to automate and when. To this end the concept of the Cognitive Workload Value factor is introduced, which takes into account both workload and situation awareness. This initial work introduces a possible framework for categorizing and using different workload and situation awareness measures.

**Keywords:** Adaptive automation, cognitive workload value, operator mental workload, situation awareness relevance, workload balancing.

## 1 Introduction

Today's industries are highly automated, sometimes to a point where the human operator is supposed to just sit back and monitor. There are many good reasons to use automation, and it is fair to say that many things we take for granted would not be possible without automation. For example, automation is executing tasks that require faster responses than humans possess (e.g. a process safety system) or accurately track many data points 24/7 without interruption.

Another common reason to use automation is to lower the workload for users by taking over the more tedious tasks so the human can focus on their main task. In their discussion of automation induced surprises, Sarter et al. [1] argue that in many cases the introduction of automation did not lower the workload, but rather produced an uneven redistribution in time. One reason for this phenomenon is that the automation introduces new tasks and associated workload. Also typically the tasks under normal circumstances, when workload is normal, are the target of automation while tasks during abnormal operation, when workload is much higher, still require a lot of manual actions which now include the additional actions required for the automation system.

Moreover, care must be taken to choose an appropriate level of automation, for taking too many tasks away from the human operator can introduce problems of its own. An operator that becomes detached from the actual processes in the plant because automation is doing practically everything will have a very hard time understanding what is going on when that automation fails ("Out-of-the-Loop

syndrome”). It could be argued that the primary role of the human operator has actually become to take over when the automation systems can’t cope with whatever abnormal situation is happening. An operator that is Out-of-the-Loop can’t perform his primary role effectively.

The balance that must therefore be considered is a tradeoff between workload and Situation Awareness. It must be noted that in this paper when we talk about workload, it means cognitive workload; physical workload is not considered and assumed appropriately designed for the operator working in a control room. For systems that have a fairly constant workload it is possible to design and choose an appropriate level of automation that will impose a manageable workload on the operator while still maintaining a good level of Situation Awareness. However, depending on the type of process, there can be large fluctuations in workload and in these cases a static level of automation will either impose a workload that is too high during peaks or too low during normal operation.

The challenge to the automation industry is to come up with systems that are able to balance workload dynamically, support the operator in maintaining high situation awareness and minimize additional automation induced workload. This initial work proposes a possible framework for dynamically selecting the level of automation for defined tasks based on a categorization of workload and situation awareness measures. It will show that this categorization is necessary to sensibly combine these workload and situation awareness measures into the newly introduced concept of the Cognitive Workload Value factor. The aim is to be practical rather than comprehensive at this point, and as this is initial work the framework will need further development and testing.

## **2 Automation mechanisms**

When tasks are automated, it is not an all-or-nothing situation choosing between completely automated or completely manual. In a dynamic environment there will be various degrees and dimensions of distribution of work between humans and machines. A system for workload balancing must therefore be able to manipulate these distributions, and we must be able to express these manipulations as a limited set of distribution choices to make it practically applicable.

### **2.1 Workload balancing mechanisms**

A fluctuating workload might be balanced by modifying the distribution in multiple ways.

- Distribution in time
- Distribution in priority
- Distribution in available processing power
- Distribution in executing entity

Distribution in time is basically a task scheduling activity. A priori knowledge of workload associated with certain tasks can be used to plan for a certain workload over time. This should be the basis of any workload balancing strategy, but does not account for unforeseen situations (like process upsets). Ad-hoc changes to the schedule might be difficult because many tasks and procedures, once started, do not allow for pausing and picking up at some point later in time. The degree to which schedules can be manipulated is highly dependent on the process so this balancing mechanism will be left alone for now.

Distribution in priority is a mechanism to help decide which tasks are most important at any given moment. This could mean that tasks that would be seen as important during normal operation change to a lower priority during critical situations and postponed to a later time or even get dropped completely. Task priority levels can be either be selected a priori by analyzing their criticality for a range of process states or scenarios. Alternatively the priority can be calculated similar to the task level situation awareness as explained further on in this paper using equations (2) and (3).

Distribution in available processing power means splitting and dividing a task between multiple executing entities. Typically this means getting more operators involved (e.g. during a plant startup). This is more suited to an operational choice by e.g. the operations supervisor instead of an automated system and is not continuously modified, but any system for workload balancing will have to be able to know how many humans are involved to correctly assign tasks between them and assign those task in a logical, coherent way for the operators.

Distribution in executing entity means choosing who will do a specific task. This can be a choice between human or automation, but also a choice between different humans. Operators often work in teams, and an operator more experienced with the task might experience a lower workload than an inexperienced operator. When the distribution is between humans and automation, the degree to which this is done can be described by the levels of automation.

## **2.2 Levels of Automation**

When talking about the level of automation it is useful to follow some defined taxonomy. One established taxonomy is by Endsley and Kaber [2], which defines 10 levels of automation implemented by four generic functions as shown in Table 1. A detailed taxonomy like this gives us a very precise way to categorize automation (sub)systems, but this level of detail might also make a practical implementation of the workload balancing that is discussed in this paper unnecessarily complex.

When manipulation of the level of automation is used a mechanism to balance workload, it is paramount that the operator understands what the automation is (or is not) doing at any given time. The interface should clearly show the tasks to be executed, with their subtasks and who is supposed to do what. Suddenly changing the level of automation halfway through a subtask would surely be confusing and lead to automation surprises [1], so the system should only be allowed to change automation levels in between (sub)tasks.

**Table 1.** Endsley and Kaber's Taxonomy for Levels of Automation

Level of Automation		Monitoring Role	Generating Role	Selecting Role	Implementing Role
10	Full automation	Computer	Computer	Computer	Computer
9	Supervisory control	H/C*	Computer	Computer	Computer
8	Automated decision making	H/C	H/C	Computer	Computer
7	Rigid system	H/C	Computer	Human	Computer
6	Blended decision making	H/C	H/C	H/C	Computer
5	Decision support	H/C	H/C	Human	Computer
4	Shared control	H/C	H/C	Human	H/C
3	Batch processing	H/C	Human	Human	Computer
2	Action support	H/C	Human	Human	H/C
1	Manual control	Human	Human	Human	Human

\* H/C: Shared between Human and Computer

A simpler but perhaps more practical model might be taken from Wickens [3]. This model defines six levels of automation and three stages of automation as shown in Table 2.

**Table 2.** Wickens' Taxonomy for Levels of Automation

Stage 1 Information acquisition and analysis		Stage 2 Decision and choice	Stage 3 Execution
High (many features)*		High Automation will:	High: Automation
		6 Choose	
		5 Choose unless human vetoes	
		4 Choose if human approves	
		3 Recommend one option	
		2 Recommend multiple options	
		1 Do nothing (human choice)	
Low (no features)			Low: Manual

\* Features of computer automation

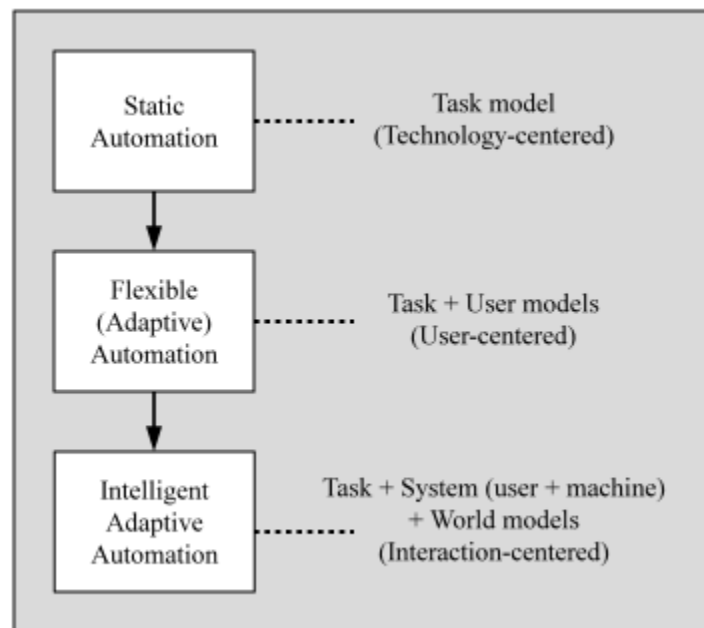
### 3 Intelligent Adaptive Automation

We now have an overview of what can be manipulated by a workload balancing system, but not yet a method for determining what should be manipulated, when to manipulate and to decide to which degree this manipulation is allowed.

Scerbo [4] discusses adaptive automation techniques that modify their level of automation based on models of operator behavior and workload, and more recently

based on psychophysiological measures [5]. These adaptation mechanisms use predefined adaptation settings that are defined for specific scenarios. This means there are inherent limits to the flexibility of such systems and much effort is needed to come up with a comprehensive and meaningful set of scenarios and decide the related automation changes. Kaber et al. [6] provide evidence that the effectiveness of adaptive automation is dependent on the stage of human-machine system information processing. The greatest effects could be seen when automation was applied to the action implementation stage and the decision making stage, while applying automation to the information acquisition stage and the information analysis stage was less effective.

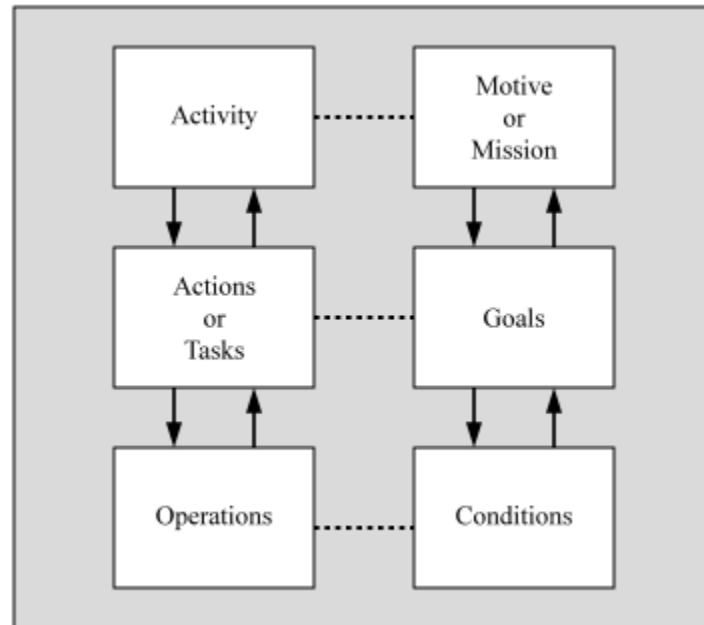
Hou, Banbury and Burns [7] introduce the idea of Intelligent Adaptive Automation (IAA) that goes one step beyond Adaptive Automation as illustrated in Figure 1. While flexible automation aims to reduce the negative effects of static automation by dynamically shifting tasks between operator and automation, it is based on task and user models only and does not take external effects into account. Intelligent Adaptive Automation explicitly adds world models so the external effects are incorporated.



**Fig. 1.** Evolution of automation technologies and their relationship to different design approaches. (Hou, Banbury and Burns, 2015)

So Task, User and World models must be connected in a systematic way to accomplish IAA. A useful way of looking at the connection of these models is by the hierarchical model of activity theory according to Kuutti [8], as illustrated in Figure 2. Humans perform activities, which consist of different actions or tasks, which in their

turn consist of operations. Human activity is driven by motives or ‘missions’, actions or tasks by goals and operations by conditions.



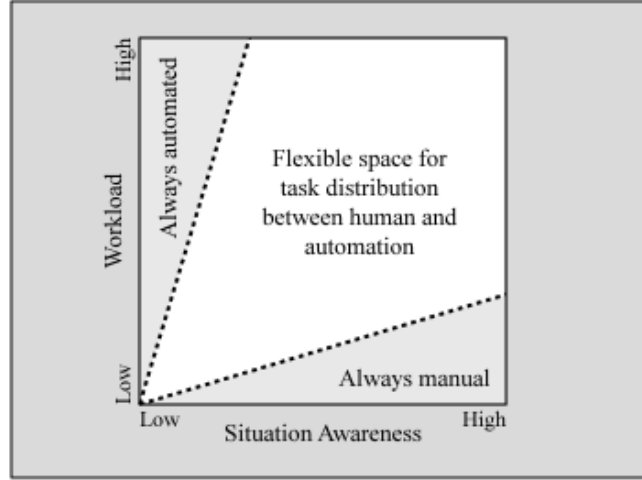
**Fig. 2.** Hierarchical model of activity theory (Kuutti, 1996)

This provides us with a model to categorize items that may be manipulated in order to balance workload. It also links these items to their drivers, so a sensible choice can be made based on the contribution to the performance of the system as described in motives, goals and conditions.

The remainder of this paper will introduce an objective method for determining the dynamic level of automation for items based on the above categorization model.

#### **4 The Cognitive Workload Value Factor**

When trying to determine what to adapt it is important to keep in mind the tradeoff between workload and situation awareness. For a specific task one can look at the workload imposed and the situation awareness provided by manually executing that task. Tasks that impose a high workload but provide little situation awareness should preferably always be automated, whereas tasks that impose little workload but provide high situation awareness should preferably always be done manually. The space of flexibility where (intelligent) adaptive automation can exist is somewhere between these extremes. This is illustrated in Figure 3.



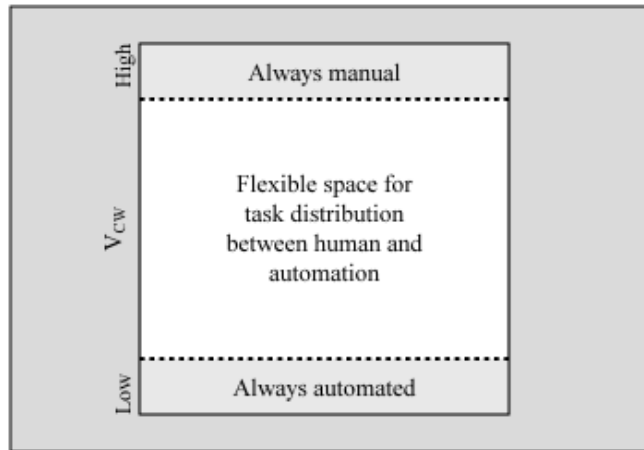
**Fig. 3.** Possible tasks available for (intelligent) adaptive automation

We now introduce the Cognitive Workload Value factor  $V_{CW}$ .

$$V_{CW} = \frac{SA}{WL}. \quad (1)$$

Where SA is some measure for situation awareness and WL is some measure for workload. Expressed in this way we can say that the higher the  $V_{CW}$  for a particular task, the more we would like this task to be manual and the lower the  $V_{CW}$  the more we would like this task to be automated.  $V_{CW}$  can therefore act as a threshold value for making decisions in adaptive automation strategies.

The inverse of  $V_{CW}$  is  $P_{SA}$ , or the Price of Situation Awareness.



**Fig. 4.** Possible tasks available for (intelligent) adaptive automation based on  $V_{CW}$



## 5 Determining the Workload Factor

Of course to use  $V_{CW}$  in a real situation, one must be able to determine the WL and SA factors of any activity, task and operation. For the argument of this paper it is not important exactly which methods are used, but we can make a distinction in the direction any WL calculation should be performed.

### 5.1 Activity Level Workload

On the *Activity* level work is driven by motives, or a ‘mission’. This puts this level mostly as an interior function of the human operator, where we need to look at *perceived* workload. The most practical way of determining this activity workload factor  $WL_A$  is by regularly asking the operator to express their perceived workload. Of course care must be taken that this probe does not significantly increase the perceived workload itself, so it should be easy to input the answer, not too often and might even be dropped when inferred or measured workload levels are very high.

### 5.2 Task Level Workload

On the *Task* level work is driven by goals that are often set on a business level. These goals and tasks are known upfront and therefore we are looking at *inferred* workload. Hou, Banbury and Burns [7] propose to use Mission, Function and Task Analysis (MFTA), which seems like a good fit because it takes into account scenarios, goals, system functions and tasks. Other possible methods could be Hierarchical Task Analysis (HTA), Cognitive Task Analysis (CTA) or Applied Cognitive Work Analysis (ACWA).

By calculating a workload factor  $WL_T$  for each known task, these tasks can be scheduled to set up a base workload over time, but not yet determine which tasks could best be offloaded to automation. This should also include very general tasks like “monitoring” and should include both main and secondary tasks.

This can be extended to subtasks to get a more fine-grained indication of workload by using subtask workload factor  $WL_{ST}$ .

### 5.3 Operations Level Workload

On the *Operations* level work is driven by interaction with the external world. These external factors need to be observed in real time and therefore we are looking at *measured* workload. We can try to measure operations workload  $WL_O$  indirectly by looking at primary or secondary task performance, where we try to correlate task performance with workload. These methods are not preferred in the context of this paper, as it might clash with the objective of actively steering workload by changing the tasks dynamically. Another method would be to use leading variables. For example the number of active alarms or mouse movement and clicks could be used to indicate a change in workload. These measurements have the benefit of being

unobtrusive and probably easily accessible by the automation system. As a third option we can try to measure workload more directly by (psycho)physiological measures. For example heart-rate, pupil dilation, galvanic skin response or electroencephalogram (EEG) can be used. However, putting measurement devices on operators permanently during their daily work might be too intrusive. Advances in consumer electronics aimed at measuring health (heart rate monitoring bracelets, smart glasses that can scan the pupil or even receive basic EEG information) could potentially make this more viable.

**Table 3.** Directions for Workload Determination

Work level	Driven by	Workload type	Method
Activity	Motives, interior	Perceived	Probe
Tasks	Goals, business	Inferred	MFTA, HTA, CTA, ACWA
Operations	Conditions, external	Measured	Leading indicators, (psycho)physiological measures

## 6 Determining the Situation Awareness Factor

Similar to the determination of the Workload factor, the Situation Awareness factor should be determined for the three different levels of work. Additionally a distinction is made between *relevant* and *irrelevant* SA.

### 6.1 Situation Awareness Relevance

Taken broadly, having high SA means knowing and understanding what is going on. For relatively simple systems this might be sufficient, however for reasonably complex systems it is safe to say that it is impossible to know and understand everything that is going on. When determining SA it is therefore important to consider what this SA applies to. For example an operator might have very high SA regarding the process of a particular unit, but if for the situation at hand the process of that unit is largely irrelevant, the cognitive work associated with maintaining the high SA is actually wasted. Furthermore, in a dynamic environment the relevance of SA for a particular part of the process can change over time. This is why the distinction between *relevant* and *irrelevant* SA is made here, which are actually the extremes of what we now define as the Situation Awareness Relevance,  $R_{SA}$ .

## 6.2 Activity level Situation Awareness

SA on the *Activity* level is related to the operator's understanding of the state of the current 'mission'. This could be for example starting up the plant. Similar to the Workload Factor we view this as a *perceived* SA. In this case we can't just ask the operator about his perceived SA, as he does not know what he doesn't know. Also ego plays a role, and it is expected that people will grant themselves high scores for SA, deserved or not. A more subtle method is probing the operator for aspects of the mission state that can be verified by the system, out of which a score can be calculated for relevant perceived SA for activities,  $R_{SA_A}$ .

The current mission can be regarded as the most relevant part of operating a plant. Therefore SA about mission state is by definition relevant.

## 6.3 Task Level Situation Awareness

Taking a similar approach, SA on *Task* level is related to the goals and we are looking for an *inferred* SA. Which goals are currently relevant is dictated by the current mission, therefore we need to determine an  $R_{SA}$  for each defined goal,  $R_{SA_G}$ .

Furthermore each task will contribute to one or more goals. For each task-goal relationship the contribution of that task to accomplishing that goal can be expressed as  $C_{G(x)}$  for goal x. The total task relevance can then be expressed as

$$R_{SA_T} = \sum_{i=1}^n C_{G(i)} R_{SA_{G(i)}} \quad (2)$$

This idea can be extended to subtasks, where each subtask's relevance is scored as contribution to the complete task  $C_T$ ,

$$R_{SA_{ST}} = C_T R_{SA_T} \quad (3)$$

## 6.4 Operations Level Situation Awareness

On the *Operations* level the SA is related to conditions, or process variables. At this level we are looking for *measured* SA. A possible measure could be the deviation of the process values from their intended values,  $D_V$ . Which process variables are relevant for SA is determined by their contribution to subtasks and the relevance of those subtasks. One process value can contribute to multiple subtasks, but only a subtask that is currently executed is actually relevant at the specific moment of measurement. Taking into account that multiple subtasks could be executed in parallel, this means that the operations SA relevance of a variable can be expressed as

$$R_{SA_V} = \sum_{i=1}^n C_{ST(i)} R_{SA_{ST(i)}} \quad (4)$$

Total relevant operational SA can then be expressed as

$$R_{SA_O} = \sum_{i=1}^n R_{SA_{V(i)}} (1 - D_{V(i)}) . \quad (5)$$

## 7 The Adaptation Threshold

We can now determine the perceived, inferred and measured  $V_{CW}$  for activities, subtasks and operations.

$$V_{CW_A} = \frac{R_{SA_A}}{WL_A} . \quad (6)$$

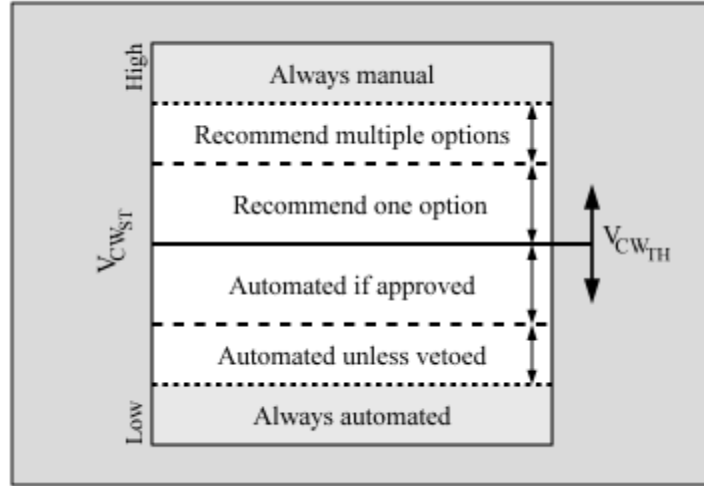
$$V_{CW_{ST}} = \frac{R_{SA_{ST}}}{WL_{ST}} . \quad (7)$$

$$V_{CW_O} = \frac{R_{SA_O}}{WL_O} . \quad (8)$$

Intelligent Adaptive Automation can use  $WL_A$  and  $WL_O$  to determine if more or less automation is needed. We assume here that automation can replace any subtask, and to determine which subtasks are executed the  $V_{CW_{ST}}$  is used by comparing it to a dynamic adaptation threshold  $V_{CW_{TH}}$ . Any subtask with a  $V_{CW_{ST}} < V_{CW_{TH}}$  should be automated.

## 8 A Workload Balancing System

If we would implement the intelligent adaptive automation by using the adaptation threshold  $V_{CW_{TH}}$  and switching subtask between completely automated and completely manual, these changes might be too drastic for the operator to keep understanding what the automation is doing. Therefore it is suggested to use the Automation Level Taxonomy from table 2 as a transient automation spectrum as illustrated in Figure 5. The central threshold can be derived from a combination of  $WL_A$ ,  $WL_O$  and a preferred workload level that can be set by the operator. In this way the operator is always in control of the level of automation.



**Fig. 5.** Intelligent Adaptive Automation scheme based on  $V_{CW}$

Finally, the system above can deal with workload that becomes too high, but what about a workload that is too low? The operator probes needed to determine  $R_{SA_A}$  can be used here in a very useful way. By asking the operator about aspects of the mission state but allowing the operator to search for the answer, the operator is encouraged to increase their relevant situation awareness. So these probes have value for the operator and we can vary the rate of probing to increase the workload in a meaningful way if required.

## 9 Conclusions and Future Research

The concept of the Cognitive Workload Value factor provides a subjective means to rank tasks on a scale linked to desired level of automation. It requires the determination of Workload and Situation Awareness factors at different activity levels. Situation Awareness is split in relevant and irrelevant SA, so as to determine the relevance factor related to current motives and goals. By combining these factors with given set of automation levels and a desired workload that can be set by the operator, the workload balancing system can start to dynamically determine levels of automation for (sub)tasks.

This method is still at a conceptual stage. The next step will be to formalize the application of the workload- and situation awareness metrics in order to be able to make the required calculations. When this is in place, a set of trial tasks can be used to test this formalized method and whether the system provides the necessary range of Cognitive Workload Values to allow dynamic behavior of the balancing system.

It might prove very difficult in practice to put sensible numbers on all tasks. Also this system expects most, if not all, tasks to be defined in the system to be most effective.

If these hurdles can be overcome, user tests will be extremely important to determine if such a dynamic system of automation actually makes sense to the user and does not impose a high additional workload in itself or confuses the user.

The concept of Cognitive Workload Value might be used in other directions of research, as it supplies a different view on workload; not all workload is equal, and not all workload is bad. Also the concept of Situation Awareness Relevance might be useful to the field of interface design, as SA is often used as a reason for design choices without acknowledging that having a high SA of everything in a complex dynamic system is impossible and that what is actually important will change over time.

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